UNIT III - CONCENTRATING COLLECTORS

Tracking systems - compound parabolic concentrators - parabolic trough concentrators - concentrators with point focus - Heliostats- comparison of various designs - central receiver systems - parabolic trough systems - solar performance analysis - solar power plant - solar furnace

1. Tracking Systems

Purpose:

Tracking systems align the solar collector with the Sun to maximize energy absorption throughout the day.

Types:

Type	Description	Example
Single-axis tracker	Moves in one axis (east–west or north–south)	Parabolic trough concentrator
Dual-axis tracker	Moves in both azimuth and altitude directions	Heliostats for central receivers

✅ **Advantages:**

- Increases daily energy yield by 25–45%
- Improves system efficiency

❌ **Disadvantages:**

- Higher mechanical complexity
- Needs regular maintenance

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2. Compound Parabolic Concentrators (CPCs)

Principle

CPCs work on the principle of **non-imaging optics**, concentrating solar radiation onto an absorber or receiver without needing the sunlight to be perfectly parallel.

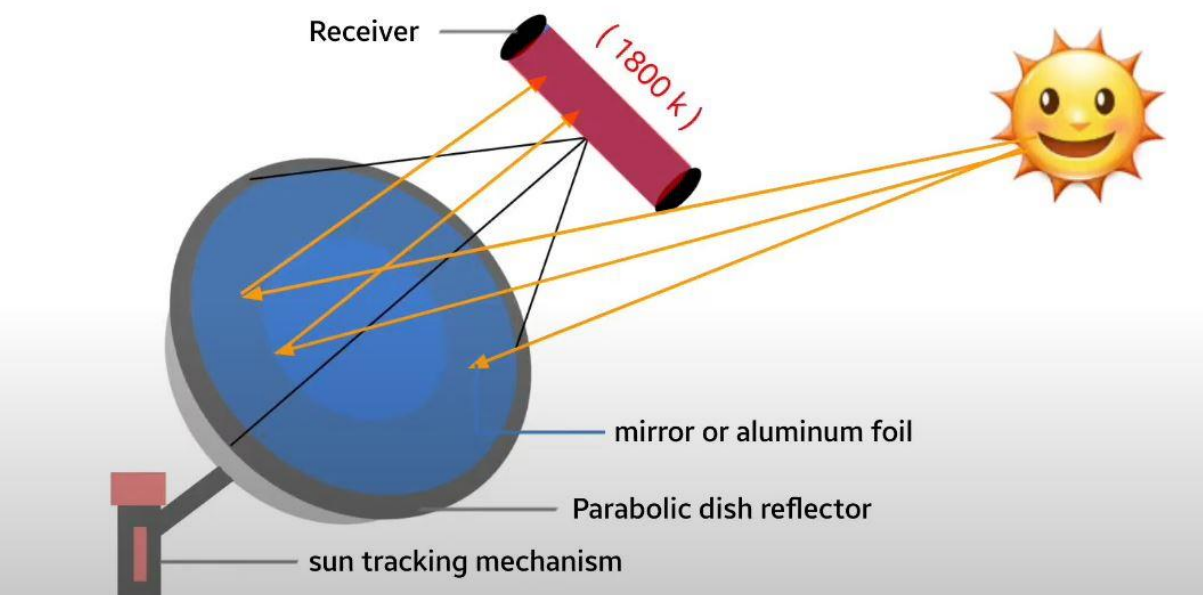
- They accept incoming solar rays **over a wider acceptance angle** and reflect them toward the **absorber tube**, even when the Sun is not perfectly aligned.
- **No tracking system** is necessary if the acceptance angle is sufficiently large.

Incoming sunlight → Parabolic reflectors → Absorber

Key Features:

- Non-imaging concentrator
- Accepts sunlight over a wider range of angles
- No tracking required

Feature	Value
Concentration Ratio	2:1 to 10:1
Temp Range	Up to 200°C



Construction (Ref. Image)

Though the image shows a **parabolic dish**, a typical **CPC** consists of:

Component	Description
Reflector Surfaces	Two symmetric parabolic mirrors designed to capture and reflect solar rays
Absorber/Receiver	Positioned at the base/focus where rays converge, typically a metal or fluid pipe
Housing/Frame	Encloses the mirrors and absorber for structure and thermal insulation
Reflective Coating	Aluminium foil or silvered mirror surface to maximize reflection

In the **dish-type shown**:

- The dish acts as a 3D parabolic reflector.
- Sunlight is focused at a **point** where the receiver reaches up to **1800 K** (as shown).

Working

1. **Solar rays** enter the collector and are reflected by the parabolic surfaces toward the absorber.
2. Unlike imaging concentrators, **CPCs work with both direct and some diffused sunlight**, thanks to their wide acceptance angle.
3. The **absorber (receiver)** collects the concentrated heat and transfers it to a **working fluid** like water or oil.
4. This thermal energy is used for **heating, drying, or electricity generation.**

Advantages

Advantage	Details
No Tracking Required	Can accept sunlight from a wide range of angles (±20° or more)
Simple & Robust	No moving parts; low maintenance
Higher Efficiency than Flat Plate	More concentrated heat with smaller absorber area
Low Cost	Easier and cheaper to build than dish/trough concentrators
Good for Low to Medium Temps	Ideal for 60–200°C applications

Limitations

Limitation	Explanation
Lower Concentration Ratio	Typically 2:1 to 10:1
Not Suitable for High Temps	Limited to medium-temp processes compared to point focus systems
Bulky Design	Wider geometry needed to cover large acceptance angles
Fixed Collector Size	Scaling beyond certain limits affects optical performance

Applications

Application Area	Example
Solar Water Heating	Domestic and commercial water heaters
Solar Cooking	Concentrated solar cookers for community use
Industrial Process Heat	Drying, pre-heating fluids in industries
Solar Desalination	Heating input water in solar stills
Greenhouse Heating	Supplementing thermal energy for controlled climate

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3. Parabolic Trough Concentrators

Principle

Parabolic Trough Concentrators operate on the principle of **line-focus solar concentration**.

- A **parabolically curved reflector** concentrates sunlight onto a **receiver tube** placed at the focal line of the trough.
- This tube carries a **heat transfer fluid (HTF)**, which absorbs the concentrated heat and transports it to a power system or thermal storage.

Sunlight → Parabolic Mirror → Focus (Receiver Tube) → HTF

Design Aspects:

- Requires **single-axis tracking**
- Used with heat transfer fluids (oil, molten salt)

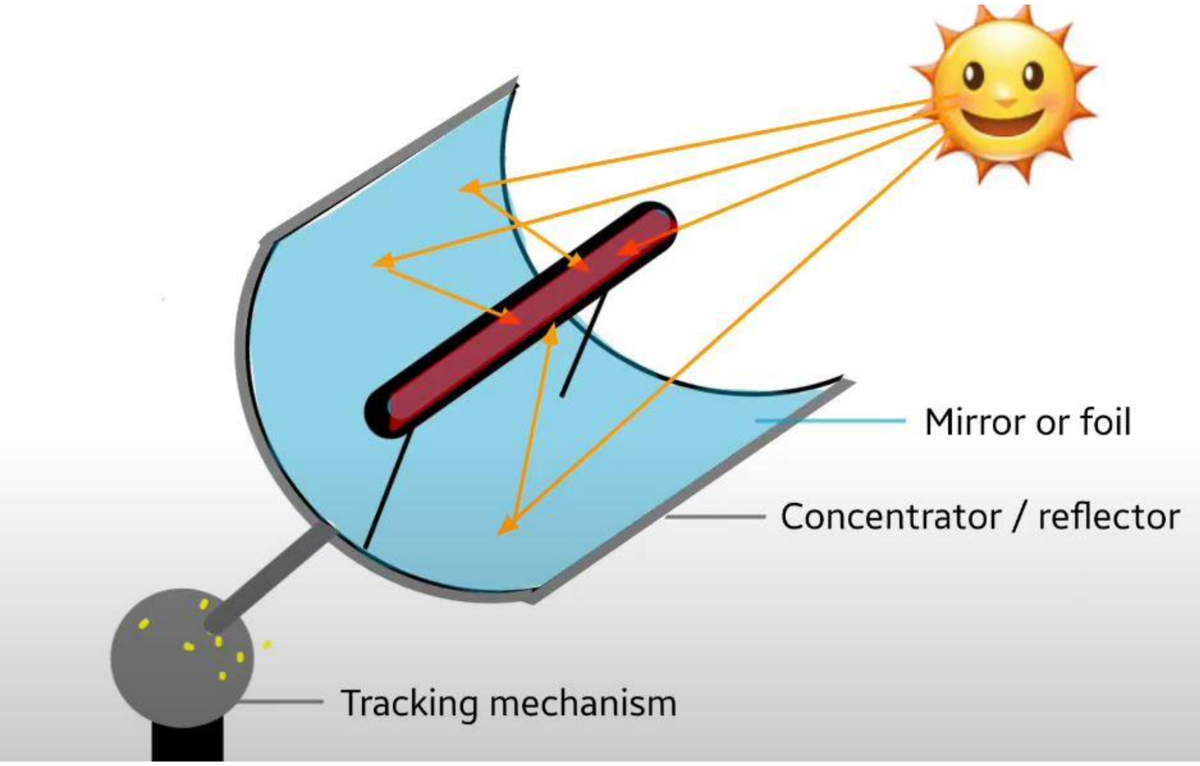
Feature	Value
Concentration Ratio	10:1 to 80:1
Temp Range	150°C to 400°C

Construction (Based on Image)

Key Components:

Component	Function
Parabolic Reflector	Made of polished aluminum or silvered glass to reflect sunlight
Receiver Tube	Located at focal line, absorbs concentrated solar energy
Mirror/Foil Surface	Reflects sunlight accurately to the focal line
Glass Enclosure (Optional)	Covers the receiver to reduce heat loss

Component	Function
Tracking Mechanism	Single-axis tracker rotates the trough east to west



Working

1. **Sunlight hits the curved mirror** and gets reflected toward the receiver tube.
2. The **receiver tube**, often coated with a selective surface, absorbs this solar heat.
3. A **heat transfer fluid (e.g., synthetic oil, molten salt, or water)** flows through the receiver tube and carries the heat to a heat exchanger or thermal storage system.
4. A **single-axis tracking system** ensures the trough always faces the Sun, maximizing energy concentration throughout the day.

Advantages

Advantage	Explanation
High Efficiency	Concentrates sunlight 30–80 times over flat collectors
Modular Design	Easy to scale by adding more troughs
Medium-High Temp Range	Generates temperatures between 150°C and 400°C
Single-Axis Tracking	Simpler than dual-axis; reduces operational complexity

Advantage	Explanation
Suitable for Power Generation	Can operate steam turbines via Rankine cycle

Limitations

Limitation	Explanation
Higher Initial Cost	Requires precision construction and alignment
Needs Precise Tracking	Even slight misalignment affects efficiency
Maintenance Required	Mirror cleaning, tracking mechanism upkeep
Less Efficient in Cloudy Conditions	Works best with direct beam radiation

Applications

Application Area	Examples
Solar Thermal Power Plants	SEGS (USA), Andasol (Spain)
Process Heat in Industries	Heating for textile, food, and dairy industries
Desalination Systems	Heating water for solar distillation
Space Heating Systems	Supplying heat to large buildings or greenhouses
Pre-heating Boiler Feedwater	Reduces fossil fuel use in conventional plants

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4. Concentrators with Point Focus

Working Principle:

Sunlight is concentrated to a **single point** using a paraboloid dish or a Fresnel lens.

Design Types:

- **Parabolic Dish:** Focuses sunlight onto a receiver at the focus point
- **Fresnel Lens:** Compact alternative using flat lenses

Feature	Value
Concentration Ratio	100:1 to 1000:1
Temp Range	Up to 1000°C

✓ Advantages:

- Highest possible temperatures
- Suitable for Stirling engines and power generation

✕ Disadvantages:

- Requires **dual-axis tracking**
- Costly and complex system

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5. Heliostats (Concentrators with Point Focus) – Central Receiver System

Definition:

Heliostats are **mirrors that track the Sun** and reflect its rays onto a fixed receiver (usually on a tower).

✓ Key Points:

- Used in **central receiver systems**
- Requires **dual-axis tracking**
- Computer-controlled for accuracy

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6. Comparison of Various Designs

System Type	Focus Type	Tracking	Temp Range (°C)	Applications
CPC	Line	No	60–200	Water heating, air heating
Parabolic Trough	Line	Single-axis	150–400	Power generation, heating
Parabolic Dish	Point	Dual-axis	Up to 1000	Stirling engine, power
Heliostat + Tower	Point (indirect)	Dual-axis	500–1000+	Utility-scale power plants

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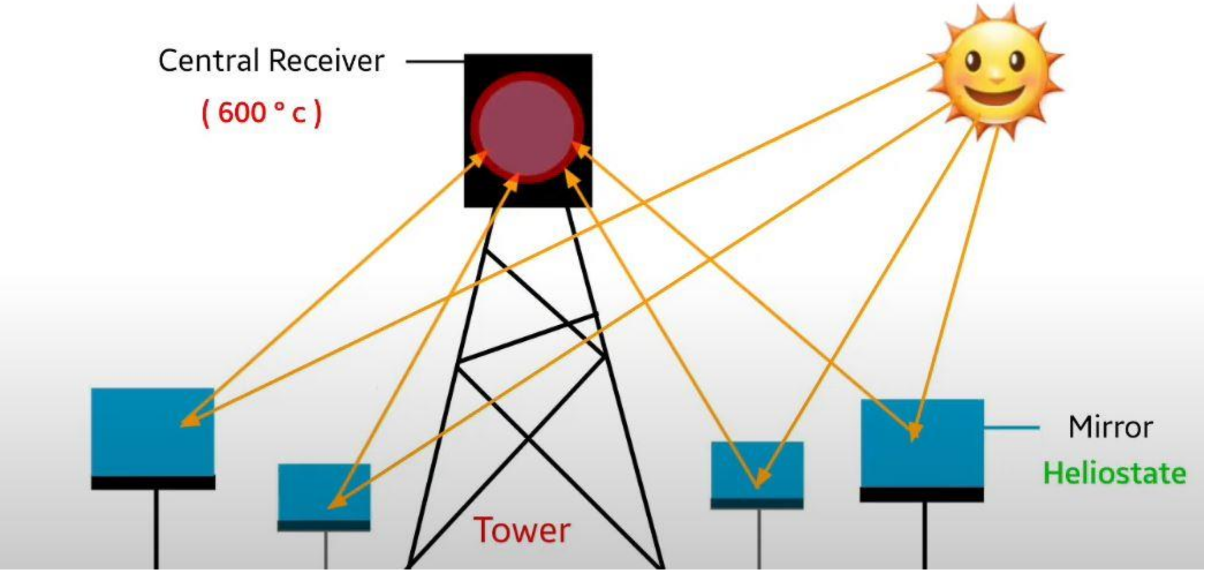
7. Central Receiver Systems (Solar Tower)

Working Principle:

- Each **heliostat** follows the Sun using **dual-axis tracking**, ensuring that reflected rays are always focused on the receiver.
- The central receiver absorbs this concentrated solar radiation and converts it into thermal energy — typically reaching temperatures of **600°C or higher**.

Construction (Ref: Diagram)

Component	Function
Heliostat Mirrors	Reflect sunlight towards the receiver (usually computer-controlled)
Central Receiver	Absorbs and stores heat (often using molten salt, air, or water)
Tower Structure	Elevates the receiver to collect sunlight from all heliostats
Sun Tracking System	Ensures accurate alignment throughout the day and year



Working Process

1. **Sunlight hits heliostat mirrors**, which are **individually motorized** to follow the Sun.
2. The mirrors **reflect and focus the sunlight** onto the **central receiver** at the top of the tower.
3. The receiver absorbs the energy and transfers it to a **heat transfer medium** (e.g., molten salt).
4. This thermal energy is then used to:
   - Generate steam
   - Drive a turbine
   - Produce electricity via a conventional **Rankine cycle**
5. Excess heat can be stored in **thermal storage tanks** for night-time or cloudy-day operation.

Advantages

Advantage	Details
High Operating Temperatures	Up to 1000°C, suitable for high-efficiency power cycles
Thermal Energy Storage	Can operate **after sunset** with stored heat (molten salt systems)
Scalable Power Output	Suitable for **utility-scale** solar power plants (>100 MW)
Large Collection Area	Single receiver collects from **thousands of heliostats**

Disadvantages

Disadvantage	Impact
High Capital Cost	Expensive due to tracking mirrors and tower infrastructure
Maintenance Intensive	Each heliostat needs regular calibration and cleaning
Weather Dependent	Requires **direct sunlight**; performance drops on cloudy days
Land Use	Requires vast land area for mirror fields

Applications

Sector	Use Case
Utility-scale power	Plants like *PS10* (Spain), *Ivanpah* (USA)
Desalination	Heating for large-scale solar desalination units
Industrial Heat Supply	Cement, metal, and chemical industries
Space Research	Solar furnace systems for high-temperature testing

Comparison between Central Receiver Systems (Solar Tower), Heliostat, and Point Focus Concentrators:

Feature	Central Receiver System (Solar Tower)	Heliostat	Concentrators with Point Focus
Primary Function	Centralized collection of solar energy	Reflects sunlight to a specific target	Focuses sunlight to a single focal point
Collector Type	Array of heliostats (mirrors)	Movable mirror	Parabolic dish or lens
Focal Point	At the top of a central tower	Depends on application (often a receiver)	At the dish's or lens's focus
Structure	Tall tower with surrounding mirrors	Flat mirror on dual-axis tracking mount	Dish-like structure, tracks sun
Sun Tracking	Yes (via heliostats)	Yes (two-axis)	Yes (two-axis)
Typical Application	Power generation in solar thermal plants	Redirect sunlight in large systems	High-temp heating, Stirling engines
Energy Concentration	Very high (multiple mirrors focused on one)	Moderate (used in coordination)	High (directly focuses solar rays)
Efficiency	High for large-scale power plants	Depends on system used	High in small-scale systems
Example Use Case	Solar thermal power stations (e.g., PS10)	Used in Solar Tower Systems	Off-grid power generation, research labs

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8. Parabolic Trough Systems

This is the **most commercially deployed CSP (Concentrated Solar Power)** technology.

System Components:

- Parabolic reflectors
- Linear absorber tube

- Tracking system
- Heat transfer fluid circuit
- Power block (Rankine cycle)

Example:

SEGS (Solar Energy Generating System), USA

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9. Solar Performance Analysis

- Solar performance analysis is the process of **quantifying the energy conversion efficiency** of solar collectors or systems.
- It involves evaluating how much of the **incident solar energy** is converted into **useful thermal energy or electricity**.

Key Performance Parameters

1. **Optical Efficiency (η_0)**
   - Represents the fraction of solar radiation absorbed by the collector without losses.
   - Depends on reflectivity, transmittance, and absorptivity of the collector.
2. **Thermal Efficiency (η_t)**

$$\eta_t = \frac{Q_u}{A_c \cdot G}$$

   Where,

   Q_u = Useful heat output (W)

   A_c = Collector aperture area (m^2)

   G = Solar irradiance on the collector surface (W/m^2)

3. **Useful Heat Output (Q□ or Q_u)**

$$Q_u = \dot{m} \cdot c_p \cdot (T_o - T_i)$$

   Where,

   m = Mass flow rate of fluid (kg/s)

   c_p = Specific heat of fluid (J/kg·K)

   T_o , T_i = Outlet and inlet fluid temperatures (°C)

4. **Concentration Ratio (CR)**

$$CR = \frac{Aperture\ Area}{Absorber\ Area}$$

    - Higher CR means more intense solar concentration, used for higher temperature applications.

5. **Tracking Accuracy**
    - Affects the alignment of collector with the Sun, directly impacting optical efficiency.

Performance Factors Influencing Output

- **Incidence Angle Modifier (IAM):** Accounts for loss due to angle of incoming sunlight.
- **Heat Loss Coefficients (UL):** Related to conduction, convection, and radiation losses from the collector.
- **Ambient Temperature and Wind:** Higher external heat losses reduce thermal efficiency.

Use in Design and Evaluation

- Performance analysis is used to:
    - **Compare collector types** (e.g., FPC, ETC, CPC, parabolic trough)
    - **Improve system design** and **collector orientation**
    - **Size storage and heat exchangers**
    - **Predict annual energy output**

This analysis is essential for validating theoretical predictions and ensuring optimal performance in real-world solar thermal systems.

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10. Solar Power Plant

A solar power plant converts solar energy into useful work—usually electricity—through thermal or photovoltaic processes. The diagram provided represents a **solar thermal power plant** using a working fluid (butane) in a **Rankine cycle** setup, specifically for **water pumping applications**, such as irrigation.

Principle

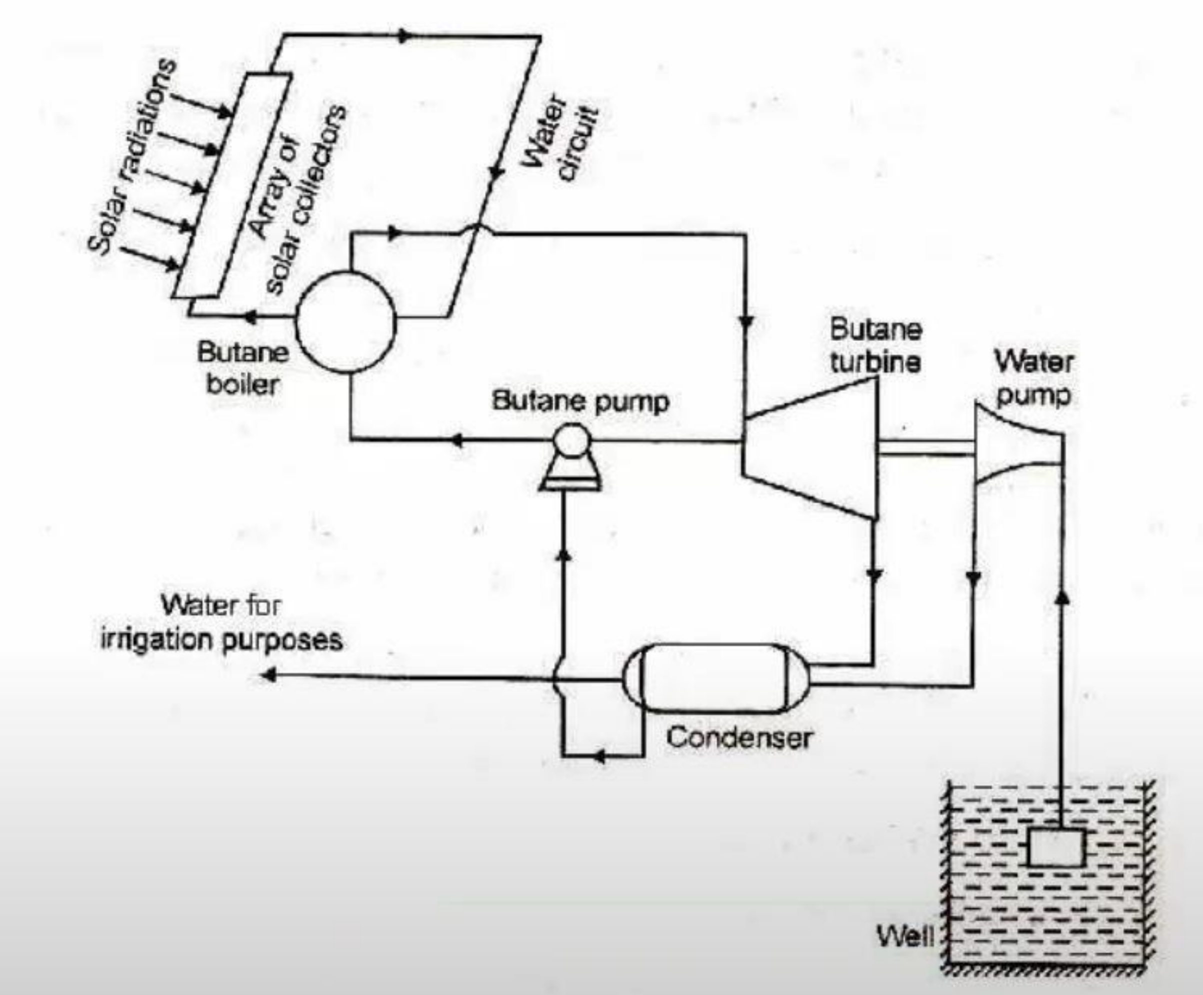
The working principle is based on the **conversion of solar radiation into thermal energy**, which is used to produce **mechanical and then hydraulic work** through a turbine and pump system.

Solar thermal power plants often operate on modified Rankine cycles using low-boiling-point fluids (e.g., butane) in **Organic Rankine Cycles (ORC)** for small-scale applications.

Components and Working

Array of Solar Collectors

- These collectors concentrate solar radiation to heat a water circuit.
- This heated water transfers energy to the **butane boiler**.



Butane Boiler

- The boiler uses the heat from the solar collectors to vaporize butane.
- Butane is selected due to its low boiling point, making it suitable for low-temperature solar applications.

Butane Turbine

- The vaporized butane expands in the turbine.
- This expansion drives the turbine and produces mechanical work.

Water Pump and Well System

- The mechanical work generated from the turbine is used to drive a **water pump**.
- The pump lifts water from a **well**, making it available for **irrigation or other purposes**.

Condenser

- After expansion, the butane vapor is condensed back into liquid in the condenser using ambient cooling water.
- The cycle continues as the **butane pump** sends the liquid back to the boiler.

Butane Pump

- Circulates liquid butane from the condenser to the boiler.
- Ensures continuous operation of the closed-loop cycle.

Advantages

- Utilizes renewable solar energy
- Zero greenhouse gas emissions during operation
- Low operating costs after initial investment
- Suitable for remote areas without grid access
- Efficient for thermal applications like irrigation, heating, and steam production

Disadvantages

- Initial installation cost is high
- System performance depends on solar availability (weather-dependent)
- Requires large land area for collector arrays
- Involves complex fluid handling and pressure maintenance
- May need backup energy source for continuous operation

Applications

- Irrigation and agricultural water pumping
- Remote and off-grid rural power systems

- Hybrid energy systems (solar + storage)
- Small-scale thermal power generation
- Industrial heating processes using organic Rankine cycles

This solar power plant diagram illustrates how **solar thermal energy** can be efficiently used with **low-boiling fluids like butane** for operating turbines and water pumps. It is particularly effective for decentralized applications such as **irrigation**, contributing to sustainable development in agriculture.

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11. Solar Furnace

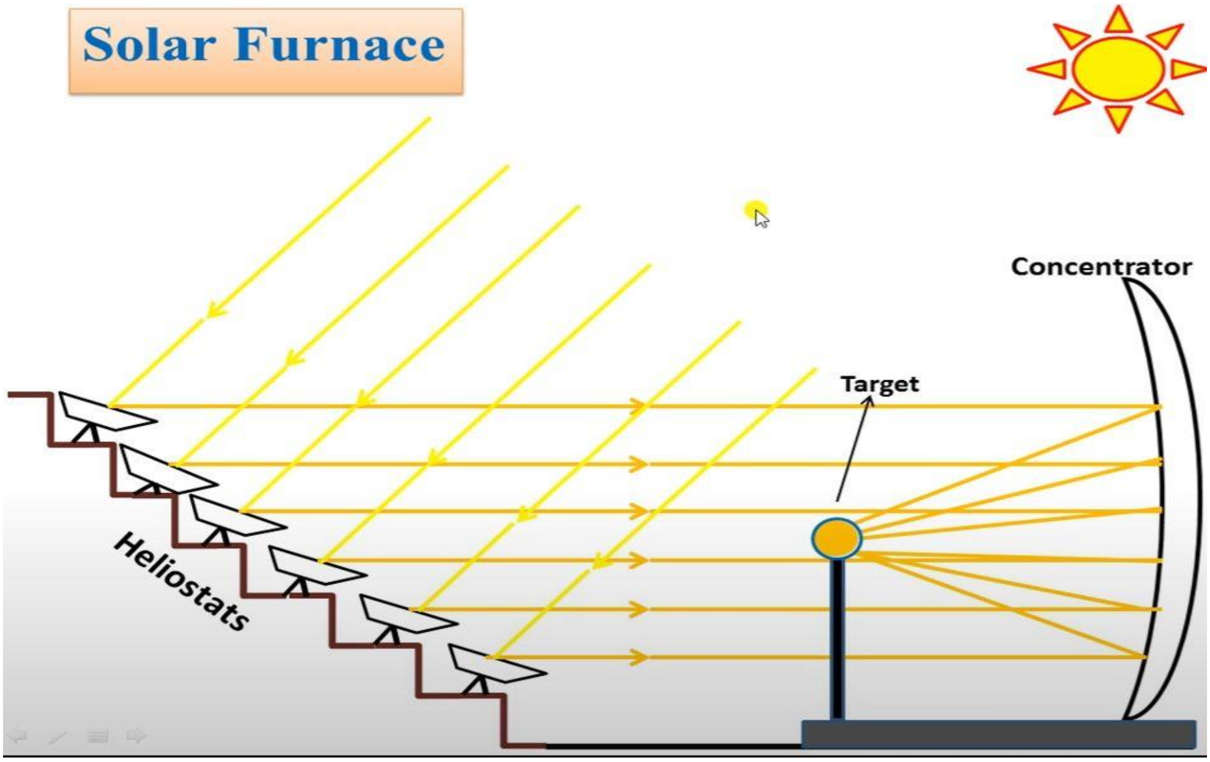
A solar furnace is a device that uses **concentrated solar energy** to produce extremely high temperatures. It operates by focusing sunlight onto a small target area using a combination of **heliostats** and a large **parabolic concentrator**. These systems can achieve temperatures exceeding **3000°C**, making them suitable for industrial and scientific applications that require intense heat.

Principle

The solar furnace works on the principle of **concentrated solar power (CSP)**. Multiple heliostats (sun-tracking mirrors) direct sunlight toward a common point, where a **large parabolic reflector (concentrator)** further concentrates the solar energy onto a **target or focal point**, drastically increasing the temperature.

Construction (Based on Diagram)

Component	Description
Heliostats	Flat mirrors mounted on tracking systems that follow the Sun and reflect rays
Concentrator	A fixed parabolic reflector that focuses incoming rays to a central target
Target	A small area where the concentrated solar energy is focused, reaching high temperatures
Support Structure	A frame or tower to hold the target and concentrator in alignment



Working

- Sunlight is first reflected by multiple **heliostats** toward the **parabolic concentrator**.
- The **concentrator reflects all the incident rays toward a single focal point**, known as the **target**.
- The energy density at the target becomes extremely high, resulting in **ultra-high temperatures**.
- This heat can be used for material testing, melting, chemical reactions, or energy conversion.

Advantages

Advantage	Explanation
Achieves extremely high temperatures	Temperatures up to 3000°C can be reached
Renewable and clean energy source	Uses solar energy without emissions
Useful for advanced research	Ideal for material science and high-temp process experiments
Precise control of heat application	Focused heating is localized and intense

Disadvantages

Disadvantage	Explanation
Weather dependent	Performance drops under cloudy or low sunlight conditions
High setup cost	Requires precision alignment and high-quality mirrors and tracking
Limited to stationary targets	Mobile heating or continuous processes are not practical
Requires large land area	Space is needed for heliostat array and mirror setup

Applications

Field	Application
Material Science	Testing of metals, ceramics, and composite materials at high temps
Solar Thermochemistry	Hydrogen production, thermochemical splitting of compounds
High-temperature Furnaces	Melting, sintering, or annealing materials
Solar Physics Research	Simulation of extreme solar conditions
Aerospace Component Testing	Thermal resistance testing for spacecraft materials

A solar furnace is a powerful tool for harnessing the intensity of solar energy in a highly concentrated form. With the ability to reach **extremely high temperatures**, it finds niche applications in **research laboratories**, **high-temperature material processing**, and **solar chemical processes**. Its operational success depends heavily on precise **heliostat alignment**, **sun availability**, and **optical design efficiency**.

Overview of Concentrating Collectors

- Concentrating collectors use mirrors or lenses to focus solar radiation onto a smaller receiver area to achieve high temperatures.
- Parabolic troughs, dishes, CPCs, and heliostat-based towers are the main types of concentrating systems.
- These systems require sun tracking (single or dual-axis) and work best with direct solar radiation.

- Capable of generating temperatures from 150°C to over 1000°C for power generation and industrial use.
- Widely used in solar power plants, solar furnaces, desalination units, and thermochemical processes.
- Enable thermal energy storage for continuous operation, even after sunset.

End Semester Questions

PART A (2 Marks Questions)

1. Infer the role of concentration ratio in performance analysis. **(April / May 2022)**
2. Compare the point and line focus collectors **(April / May 2022)**
3. State the working principle of the solar pond. **(April / May 2023)**
4. Infer the importance of heliostat design for the harvesting of solar energy. **(April / May 2023)**
5. Classify the concentrating collectors. **(April / May 2024)**
6. List the advantages of a solar furnace. **(April / May 2024)**

PART B

1. Outline the working of central power receiver systems with a neat layout **(April / May 2022)**
2. Compare the advantages and working principle of parabolic trough concentrator collectors with a neat sketch. **(April / May 2022)**
3. Interpret the need for tracking systems in parabolic trough collectors along with the working of a solar power plant with a neat sketch. **(April / May 2022)**
4. (i) Discuss the various parabolic trough concentrators with relevant sketches with its advantages and disadvantages.

   (ii) What is collector efficiency? Compare the efficiencies of different types of collectors. **(April / May 2023)**
5. Construct the need for a solar power plant and Solar furnace with its working principle and layout. **(April / May 2023)**
6. Recall the working principle of a compound parabolic collector. **(April / May 2024)**
7. Examine the environmental impact of solar power generation. **(April / May 2024)**